Subsurface Flow Component for AnnAGNPS

Y. Yuan, R. L. Bingner, F. D. Theurer

Abstract. *The Annualized Agricultural Non-Point Source Pollutant Loading (AnnANPSPL) model is a watershed scale, continuous simulation, daily time step model that is currently utilized in many locations of the United States by the Environmental Protection Agency, Natural Resources Conservation Service, and others to estimate the impact of best management practices on non-point source pollution. The model has many unique and powerful capabilities, but prior to AnnAGNPS version 2.2, subsurface lateral flow and subsurface drainage features were not available. Subsequently, subsurface lateral flow, including a subsurface drainage feature, was incorporated into AnnAGNPS and is described in this article. Subsurface lateral flow was defined based on Darcy's equation and subsurface drainage was determined using Hooghoudt's equation. Users have several options available within AnnAGNPS to determine the impact of subsurface drainage based on the availability of information on the drainage system. Subsurface lateral flow and subsurface drainage were assumed to occur only when the soil becomes saturated. As part of an inter-agency sedimentation project, the model with the subsurface enhancements was applied to the Ohio Upper Auglaize watershed non-point source modeling project to evaluate alternative agricultural management scenarios in reducing soil erosion and sediment loading within the watershed. The application illustrated the importance of including subsurface capabilities in watershed models by indicating that subsurface drainage systems within the watershed increased total runoff, but reduced direct surface runoff that, in turn, reduced soil erosion and sediment delivery from the watershed. Sediment loadings for drained conditions were less than loadings for un-drained conditions in all simulated scenarios; and the sediment loadings for drained conditions were reduced by 7% to 16% compared with un-drained conditions. Furthermore, the model indicated that application of various areas of no-till or grassland to the watershed could reduce the sediment loading transported from the watershed to a range of 39% to 82% of the existing condition.*

Keywords. *AnnAGNPS, Subsurface drainage, Model simulation, Best management practices, Sediment reduction.*

Numerous hydrologic and water quality models have been developed during the past two decades to assist in understanding basic hydrologic processes. Those models are frequently used to analyze data and are used as tools to predict the impact of changes in watershed attributes on water quantity and quality.

Watershed simulation models have proven to be effective tools for evaluating watershed management efforts (Mitchell et al., 1993; Rosenthal et al., 1995; Arnold and Allen, 1996; Spruill et al., 2000; Arnold et al., 2001; Bhuyan et al., 2001; Yuan et al., 2001a). The Annualized Agricultural Non-Point Source Pollutant Loading model (AnnAGNPS) is one such advanced technological watershed management evaluation tool. The development of AnnAGNPS has been through a partnering project with the United States Department of Agriculture (USDA) – Agricultural Research Service (ARS) and Natural Resources Conservation Service (NRCS) to aid in the estimation of watershed response to agricultural management practices (Bingner et al., 2003).

AnnAGNPS is a watershed scale, continuous simulation, daily time step model. It has been developed as a replacement for the single-event model, AGNPS (Young et al., 1989). AnnAGNPS includes significantly more advanced features, but retains many of the key elements of AGNPS (Bingner et al., 2003). Because of the continuous nature of AnnAGNPS, daily climate information, which includes daily precipitation, maximum and minimum temperatures, dew point temperature, cloud cover, and wind speed, is needed to account for temporal variation in the weather. The spatial variability of soils, land use, and topography within a watershed is accounted for by dividing the watershed into many homogeneous, drainage-area-based cells (computational areas). Runoff, sediment, and chemicals are routed from each cell through a channel network to the outlet of the watershed.

The model is currently utilized in many locations of the United States by the Environmental Protection Agency, NRCS, and others to estimate the impact of best management practices (BMPs) on non-point source pollution. The model has many unique and powerful features, some of which are: 1) efficient computation; 2) considerable spatial detail; 3) ready availability of most inputs through NRCS and other agencies' databases; 4) the capability of simulating land management scenarios (Yuan et al., 2001a); and 5) the ability to track the source and relative contribution of pollutants down through the channel network to the outlet of the watershed. However, until recently, AnnAGNPS (previous to

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version 2.2) simulated surface runoff with percolation as the only subsurface flow process, with no subsurface lateral flow, subsurface drainage, or baseflow. This gap between surface and subsurface processes is present in many hydrologic and water quality models, and few models simulate impacts of both surface and subsurface flow on water quality (Singh and Frevert, 2002).

It had been previously assumed within AnnAGNPS that percolation below the soil profile would be lost from the system and ignored. Thus, subsurface lateral flow or subsurface drainage was not simulated. However, these flows can be significant in areas with soils having high hydraulic conductivities in surface layers and a water-restricting layer below. For instance, in most areas of the Midwest, the agricultural fields are so flat that the predominant flow to surface water is subsurface seepage or subsurface drainage to channels (Mitchell et al., 2001; Yuan et al., 2001b); thus, capability of simulating subsurface lateral flow or subsurface drainage is critical when the model is applied to the watershed with drained landscapes. In addition, when simulating the effects of riparian buffer systems on water quality, the simulation of these subsurface flow conditions is important because subsurface lateral flow in riparian areas plays a significant role in filtration of nutrients and pesticides from upland agricultural areas (Lowrance et al., 1997).

The objectives of this article are to describe the development of subsurface lateral flow and subsurface drainage processes incorporated within AnnAGNPS and to examine a case application that illustrates the impact of subsurface drainage on watershed hydrology and water quality for a watershed in Ohio.

Methods and Procedures

Hydrologic Component within AnnAGNPS

The hydrology components within AnnAGNPS are based on the water balance equation, which incorporates a simple bookkeeping of inputs and outputs during a day. The original equation was:

$$SM_{t+1} = SM_t + \frac{WI_t - Q_t - PERC_t - ET_t}{Z} \qquad (1)$$

where

SM_t = soil moisture content (mm/mm) for each soil layer at beginning of time period (t)
SM_{t+1} = soil moisture content (mm/mm) for each soil layer at end of time period (t)
WI_t = water input (mm) for time period t, consisting of precipitation or snowmelt plus irrigation water irrigation water
Q_t = runoff (mm) for time period (t)
$PERC_t$ = percolation of water (mm) out of each soil layer during time period (t)
ET_t = evapotranspiration (mm) during time period (t)
Z = thickness of soil layer (mm)

The water balance is computed for two AnnAGNPS composite soil layers. The first layer is 203 mm in depth from the surface, typically termed as the tillage layer defined by the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997). The second layer is from the bottom of the tillage layer to either an impervious layer or the user-supplied depth of the soil profile.

AnnAGNPS is a daily time step model. However, because of the strong nonlinear dependence of the rates of percolation and evapotranspiration on soil water content, the daily time step can be too large to simulate percolation and evapotranspiration adequately. Therefore, soil moisture is calculated using sub-daily time steps. The day is divided into several time steps of equal length, and the water input is considered to be uniform during the course of the day. The number of time steps within a day can be specified by the user, with a default value of eight time steps in a day, which results in 3-h time steps. Other watershed models, such as the Soil and Water Assessment Tool (Arnold et al., 1998), deal with this issue by dividing daily water input into 4-mm increments and routing these increments separately.

The soil moisture (SM) is considered to be valid for the beginning of a day, while the inputs and outputs occur during the course of the day. The water input (WI) includes snowmelt, precipitation, and sprinkler irrigation water. The runoff (Q) is determined using the Soil Conservation Service (SCS) Curve Number method (SCS, 1985). For the second soil layer, the water input (WI) is the percolation from the first layer (percolation is the downward drainage of soil water into lower layers by gravity), and runoff (Q) is zero. Evapotranspiration is calculated using the Penman equation (Penman, 1948; Jenson et al., 1990). Subsurface lateral flow and drainage have not been previouslyconsidered.

Review of Subsurface Flow Processes

The infiltration of water from the soil surface to where subsurface lateral flow or subsurface drainage occurs is a complex process and can be difficult to predict. Some of these processes include infiltration during a rainfall event, redistribution of soil water, subsurface lateral flow when water accumulates above the impermeable layer forming a saturated zone of water, and subsurface drainage flow when the perched water table has risen above the level of the drain pipes.

Darcy's equation is a widely used and accurate description of water flow in soils. In general, it applies to saturated flow and unsaturated flow, steady state flow and transient flow, flow in homogeneous systems or heterogeneous systems, and flow in isotropic media or anisotropic media (Freeze and Cherry, 1979). Therefore, Darcy's equation was chosen to simulate subsurface lateral flow, and only the saturated condition is considered within AnnAGNPS. The one-dimensional form of Darcy's equation is shown below:

$$q_{lat} = -K_s \frac{dh}{dx} \qquad (2)$$

where

q_{lat} = subsurface lateral flow (mm per time step)
K_s = saturated lateral hydraulic conductivity for each soil layer (mm per time step)
dh/dx = hydraulic gradient (unitless)
h = hydraulic head (mm)

Subsurface flow to drains can be described using steady state or unsteady state flow equations. Steady state flow equations assume that a steady constant flow occurs through the soil to the drains. Discharge equals percolation, and the pressure head is constant with time. In the non-steady state formula, these parameters vary with time (Smedema and Rycroft, 1983). In most cases, subsurface drainage can be modeled assuming steady state conditions.

Hooghoudt's equation, which assumes steady state flow to drains, was chosen to simulate subsurface drainage in AnnAGNPS because of its wide applicability and relatively simple structure (Smedema and Rycroft, 1983). In the Hooghoudt equation, the perched water table above parallel drains is often approximated using an elliptical shape, as shown in figure 1. Streamlines between two parallel pipe drains typically exhibit the pattern depicted in figure 1; flow towards the drains is horizontal between the drains, and then the flow converges radially to the drain. The extent of the two flow zones differs from case to case depending especially upon the drain spacing (L), the midpoint water table height above the drains (m), and the equivalent depth of the impermeable layer below the drains (d). When L is large in comparison with both m and d, the flow is predominantly horizontal; but an extensive radial flow sector is to be expected when d is large (van Schilfgaarde, 1974).

Hooghoudt's equation, which considers both radial and horizontal flow to model the practical case of flow to drains, is shown below:

$$q_{drain} = \frac{8K_s d_e m + 4K_s m^2}{L^2} \tag{3}$$

where

q_{drain} = drainage flux (mm per time period)
K_s = saturated hydraulic conductivity (mm per time period)
L = distance between drains (m)
m = midpoint water table height above the drain (m)
d_e = equivalent depth of the impermeable layer below the drain (m)

The equivalent depth, d_e, is computed using equation 4 when the actual depth, d, to the impermeable layer is such that $0 < d/L < 0.3$ (Skaggs, 1980).

$$d_e = \frac{d}{1 + \frac{d}{L}\left[\frac{8}{\pi}\ln\left(\frac{d}{r}\right) - \alpha\right]} \tag{4}$$

where

d = actual depth of the impermeable layer below the drain (m)
r = radius of the drain tube (m)
α = a constant defined by equation 5:

$$\alpha = 3.55 - \frac{1.6d}{L} + 2\left(\frac{d}{L}\right)^2 \tag{5}$$

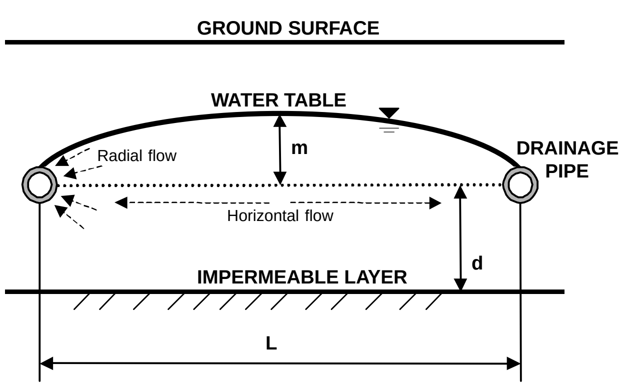

Figure 1. Representation of subsurface drainage flow.

For $d/L > 0.3$, d_e can be computed using equation 6 (Skaggs, 1980).

$$d_e = \frac{L\pi}{8\left[\ln\left(\frac{L}{r}\right) - 1.15\right]} \tag{6}$$

Subsurface Flow Simulation Procedures

After reviewing the background information of subsurface flow processes, subsurface lateral flow and subsurface drainage flow were incorporated into AnnAGNPS through the following calculations:

1. Calculate the depth of saturation (h) from the bottom of the second soil layer
   For the second soil layer:

$$SM_{t+1} = SM_t + \frac{WI_t - PERC_t - ET_t}{Z} \tag{7}$$

Soil moisture (SM_{t+1}) is compared with field capacity (FC); and if SM is less than FC, the SM for the next time step is calculated. If the SM is greater than the FC, the amount of "drainable" soil water (i.e., water in excess of field capacity) ΔSW is:

$$\Delta SW = SM_{t+1} - FC \tag{8}$$

and

$$h = \frac{(SM_{t+1} - FC)\times Z}{(PO - FC)} \tag{9}$$

where h is the depth of saturation from the bottom of second soil layer, PO is the porosity of the soil layer, and Z is the thickness of the soil layer.

Subsurface lateral flow is calculated using Darcy's equation. The hydraulic gradient is approximated by the local surface topographic slope, which was used by the TOPMODEL (Beven et al., 1995). Because the soil profile is assumed as isotropic, the saturated lateral hydraulic conductivity K_s is the same as the saturated vertical hydraulic conductivity which has been estimated in percolation (Bingner et al., 2003).

2. Calculate q_{drain}
   When the depth of saturation from the bottom of the second soil layer h is above the depth of the drainage system or the controlled drainage water table if a controlled drainage structure is applied, subsurface drainage by a pipe, q_{drain}, is calculated based on the following conditions provided by the user.
   a) If pipe spacing, pipe depth, depth to the impervious layer, and pipe diameter or radius are supplied by a user, equations 3, 4, 5, and 6 are utilized in calculating subsurface drainage flow.
   b) If only pipe spacing, pipe depth, and depth to the impervious layer are supplied, equation 3 is utilized, and the effective depth is assumed to be the same as the depth to the impervious layer.
   c) If none of the parameters is supplied by a user and if the user can supply the drainage rate (mm/h) based on local common design features, the user-supplied drainage rate is utilized.

d) If none of the information is supplied by a user, 12.7 mm/day of drainage is assumed. For example, 0.53 mm/h or 1.6 mm for 3 h would be used for a simulation with eight time steps during a day.

3. Calculate soil moisture for the next time step

Soil moisture for the next time step is calculated based on the following equation:

$$SM_{t+1} = SM_t + \frac{WI_t - PERC_t - ET_t - q_{drain} - q_{lat}}{Z} \quad (10)$$

Then steps 1, 2, and 3 are repeated if there is any subsurface lateral flow and/or subsurface drainage.

The amount of subsurface lateral flow and/or subsurface drainage taken out of each computational area (drainage−area-based) is added to the stream reach at the same time as runoff (no subsurface lateral flow and subsurface drainage between computational areas). Subsurface lateral flow and subsurface drainage flow are differentiated from groundwater (base flow) in that groundwater is considered as a slow return flow to the stream reach.

Application of AnnAGNPS

Project Introduction

The utilization of the subsurface flow components of AnnAGNPS to evaluate the impact of subsurface drainage systems was necessary within the Upper Auglaize (UA) watershed agricultural non-point source modeling project. An interagency effort was formed for this project to use a Geographic Information System (GIS)-based approach for assessing and reducing pollution from agricultural runoff and other non-point sources using AnnAGNPS. This project originated as part of the Toledo Harbor Study Team initiative to solve the problem of disposing of dredged material from Toledo Harbor where reduction of sediment entering the harbor from non-point sources would be important. The U.S. Army Corps of Engineers and the Port of Toledo spend approximately \$2.2 million to dredge 650,000 m^3 of sediment from Toledo Harbor each year. Environmentally acceptable alternatives may be less costly than dredging. A significant amount of the sediment dredged originates from farms. Therefore, a long-term goal has been established to reduce dredging by 15% through the increased use of soil erosion control techniques. AnnAGNPS was applied to the UA watershed, a major watershed within the Maumee River Basin, to identify sediment sources and contributing locations, as well as to simulate conservation treatment strategies and develop BMPs for the watershed to reduce sediment loadings.

The goal of the project was to evaluate the long-term effects of conservation practices on reducing sediment within the watershed. Since historical weather data were not available for a long-term analysis and validation study, synthetic weather data were developed for a 100-year period, providing the relative impact of precipitation, temperature, dew point, cloud cover, and wind speed within the watershed. The lack of historical weather data prevented a validation analysis for the watershed, but the main effect of subsurface drainage systems on the watershed could still be evaluated to demonstrate the importance of developing subsurface capabilities within AnnAGNPS.

The Upper Auglaize Watershed Description

The UA watershed is located in the southern portion of the Maumee River Basin (fig. 2). The watershed encompasses 85,812 ha upstream of the Fort Jennings U.S. Geological Survey (USGS) gaging station at the outlet (fig. 2). Land use is predominately agricultural with 74.2% cropland, 10.8% grassland, 6.2% woodland, and 8.8% urban and other land uses. Corn and soybeans are the predominate crops grown in the watershed and together account for an estimated 83% of the agricultural cropland in cultivation and 62% of the total watershed area. Land-surface elevations in the UA watershed range from about 233 to 361 m above sea level. Most soils in the UA watershed are nearly level to gently sloping; however, moraine areas and areas near streams can be steeper. In general, soils in the lower one-third of the watershed tend to be appreciably flatter than those in the upper two-thirds of the watershed. Blount and Pewamo are major soil types in the watershed. These soils are characterized as somewhat poorly to very poorly drained with moderately slow permeability. Therefore, agricultural fields in the watershed are artificially drained to improve crop production. Subsurface drainage (tile drainage) systems have been installed to extend and improve drainage in areas serviced by an extensive network of drainage ditches. Common conservation practices applied in the watershed include grassed waterways, subsurface and surface drainage, conservation-tillage and no-tillage, grass filter strips, and erosion control structures.

Input Preparation of Existing Watershed Conditions

Various GIS data layers of the watershed are needed for the AnnAGNPS model. These include data on land surface topography, soils, land use, stream network, and climate. These kinds of data should be defined across the study area in sufficiently spatial detail to permit the model to accurately reflect the real landscape it represents.

Using the GIS digital data layers of digital elevation model, soils, and land use, a majority of the large data input requirements of AnnAGNPS were developed by using a customized ArcView GIS interface (Bingner, 2003). Inputs developed from the ArcView GIS interface include physical information of the watershed and subwatershed (AnnAGNPS cell), such as boundary and size, land slope and slope direction, and channel reach descriptions. The ArcView GIS interface also assigned a soil and land-use type to each cell by using the generated subwatershed and the soil and land-use GIS data layers. Additional steps to provide the model with the necessary inputs included developing the soil layer attributes to supplement the soil spatial layer, establishing the different crop operation and management data, and providing channel hydraulic characteristics. Those inputs can be organized using the AnnAGNPS Input Editor (Bingner, 2003), a graphical user interface designed to aid users in selecting appropriate input parameters.

Climate data for AnnAGNPS simulation can be historically measured, synthetically generated using the climate generator program (Johnson et al., 2000), or created through a combination of the two. One-hundred-year synthetic weather data were developed and used for all simulations in this study because historical weather data were not available. Complete information on weather generation can be found at the AGNPS web site (www.ars.usda.gov/Research/docs.htm?docid=5199).

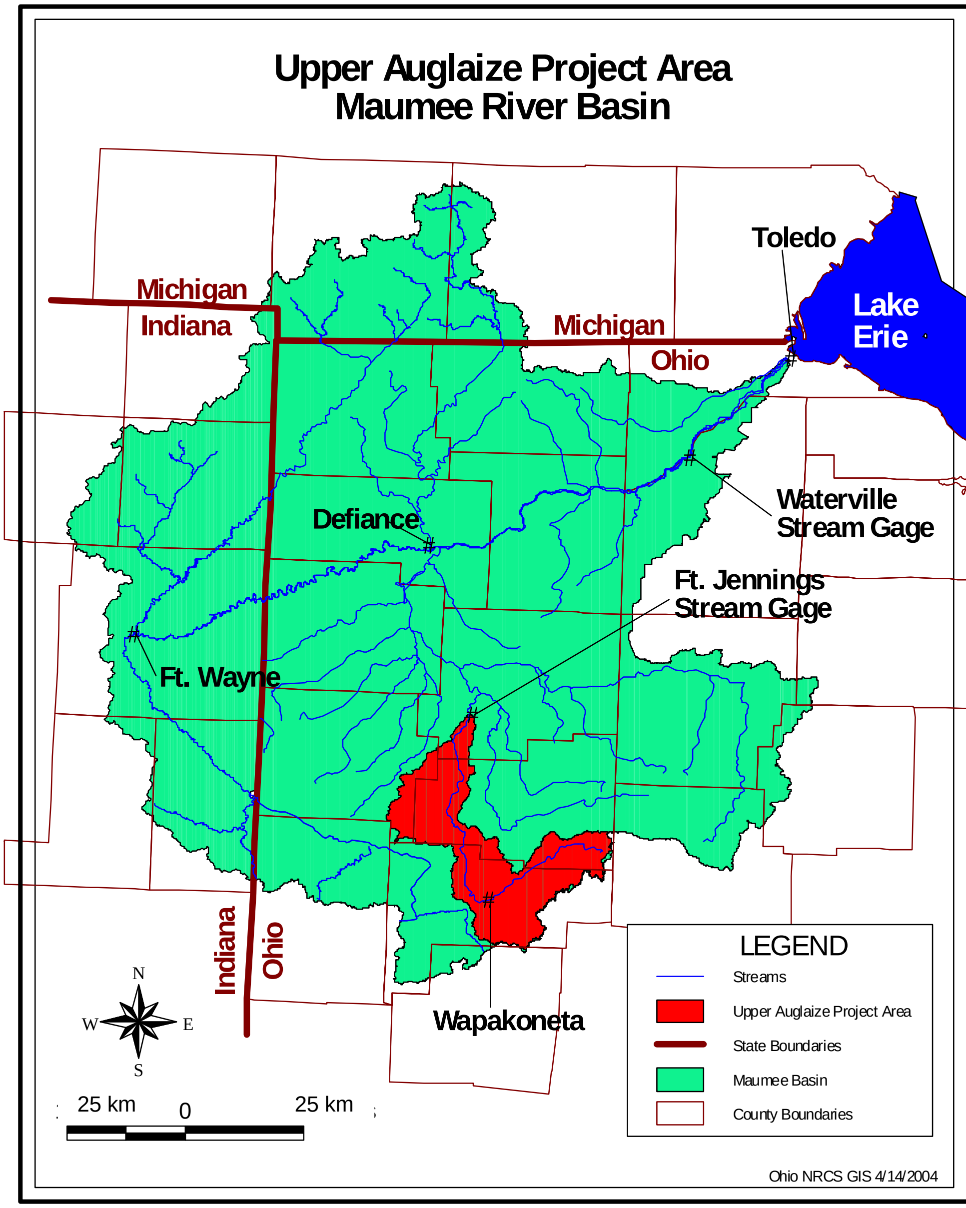

Figure 2. The Maumee River basin drainage network, Upper Auglaize watershed, and the Ft. Jennings Gage Station at the outlet of the Upper Auglaize watershed.

The characterization of the UA watershed land use, crop operation, and management during the simulation period was critical in providing estimates of the sediment loadings. AnnAGNPS has the capability of simulating watershed conditions with changing land use and crop management over the simulation period. However, it was very difficult, at this watershed scale, for AnnAGNPS to characterize the annual changes, including land use and field management practices, occurring in the watershed. The input for existing conditions of the watershed was established by using 1999-2002 LANDSAT imageries and a 4-year crop rotation derived by summarizing field records from 1999-2002. Tillage type was applied on a random basis to each field to come up with the total amount of conventional, mulch, and no-till percentages implemented in the watershed during 1999-2002 becausethe overall percentages of tillage types were known while the exact field-by-field values were unknown at this watershed scale. Percentages of tillage and land use for the UA watershed during 1999-2002 are summarized in table 1.

The AnnAGNPS parameter of curve numbers was selected based on the *National Engineering Handbook*, section 4 (SCS, 1985). Crop characteristics and field management practices for various tillage operations were developed based on RUSLE (Renard et al., 1997) guidelines and local RUSLE databases. AnnAGNPS allows for subsurface drainage systems to be simulated or not to be simulated for any given field during the model simulations. Since detailed information on subsurface drainage systems such as pipe location and pipe size was not available, it was impossible to differentiate at the watershed scale which computational areas contained subsurface drains or not, and the depth and spacing of the drainage system. Local experience substantiated that most fields in the watershed were subsurface drained to a very large extent. Therefore, the model was run

Table 1. Upper Auglaize watershed 4-year crop, tillage, and land-use distribution in percent.[a]

Land Use	Tillage	1999 (%)	2000 (%)	2001 (%)	2002 (%)
Corn	Plow	10.1	13.1	10.5	10.5
	Mulch till	18.7	17.0	20.3	17.9
	No till	10.4	14.1	12.2	14.0
	Total	39.3	44.2	43.0	42.3
Beans	Plow	8.7	6.0	7.4	9.4
	Mulch till	9.6	16.8	11.5	13.7
	No till	11.8	11.1	13.7	11.2
	Total	30.0	33.9	32.5	34.2
Wheat	Plow	1.9	2.6	3.7	1.6
	Mulch till	5.3	3.8	4.3	2.7
	No till	5.2	4.6	3.1	3.8
	Total	12.4	10.9	11.1	8.0
Grass	Plow	1.4	0.4	0.5	0.6
	Mulch till	4.2	0.2	1.7	3.7
	No till	2.7	0.4	1.1	1.2
	Continuous	0.4	0.4	0.4	0.4
	Total	8.7	1.4	3.7	5.8
Forest		5.6	5.6	5.6	5.6
Residential		2.0	2.0	2.0	2.0
Roads		1.4	1.4	1.4	1.4
Commercial		0.5	0.5	0.5	0.5
Water		0.1	0.1	0.1	0.1
Grand Total		100.0	100.0	100.0	100.0

[a] The total area is 85,812 ha.

with subsurface drainage simulated in all AnnAGNPS cells, and no specific information was entered to characterize subsurface systems; a constant drainage rate was assumed for all AnnAGNPS cells.

Development of Alternative Agricultural Management Scenarios

A significant benefit in using watershed models in conservation planning is the capability to apply and evaluate various management practices on the same landscape. For the UA watershed study, various alternative agricultural management scenarios were developed for simulation and evaluation. Local NRCS personnel recommended that no-till conservation practices replace conventional and mulch tillage practices in agricultural producer's management schedules where they could be appropriately applied. Since no-till conservation practices may not be applied in every agricultural circumstance because of economic or local issues, various levels of no-till application throughout the watershed were evaluated. Using the existing watershed management (Scenario A) as a baseline, all AnnAGNPS cells were sorted based on their highest erosion rate and grouped into categories that represented 22%, 45%, 66%, and 100% of the highest eroding cells in the watershed based on local NRCS recommendations. No-till conservation practices could then be defined for each cell according to the existing conditions. As a result, of the 22% of the highest eroding cells, only 11% of the watershed (Scenario B) required a change to no-till practices, since the other portions of the 22% of the watershed already had no-till applied. Similarly, of the 45% and 66% of the highest eroding areas, only 23.2% (Scenario C) and 35.7% (Scenario D), respectively, of the watershed required a change to no-till practices. A scenario was also evaluated where all of the cropland utilized no-till (Scenario E).

While an evaluation of no-till conservation practices is important for NRCS, the Conservation Reserve Program (CRP) is also a key component of NRCS conservation efforts. A significant aspect of CRP implementation on which NRCS would like information is how much impact this program's adoption would have on the erosion within the watershed. NRCS personnel in Ohio recommended that simulations be completed to evaluate their impact on reducing erosion that would account for CRP adoption rates of 10%, 20%, and 30% of the watershed. The primary areas where NRCS requested CRP be adopted are cropland areas in higher sloping fields. Thus, all AnnAGNPS cells were arranged by slope in the 10% (Scenario H), 20% (Scenario I), and 30% (Scenario J) categories, and cultivated cells within each category were converted to CRP land represented as grassland. Any existing grassland-defined cells within each category would remain as grassland. As a result, of the 10% of the highest slope areas, only 7.1% of the watershed (Scenario H) required a change to grassland, since the other portions of the 10% of the watershed were already grassland. Similarly, of the 20% and 30% of the highest slope areas, only 15.7% (Scenario I) and 24.5% (Scenario J), respectively, of the watershed required a change to grassland.

An alternative conservation scenario, which was also recommended by NRCS, was to evaluate the impact on reducing erosion by adopting 13% more no till and 7% more CRP land on the existing condition of the watershed. This alternative was achieved by randomly applying conservation practices throughout the watershed to the AnnAGNPS cells with the result that 12.9% more of the watershed was converted to no-till and 6.9% was converted to CRP land (Scenario G) because the irregular-shaped AnnAGNPS cells prevented an exact area match to the NRCS goal. Since Scenario G was only to evaluate the effect of what NRCS determined would be an achievable conservation level within the watershed, the simulated areas converted to conservation practices were acceptable to NRCS.

In general, scenarios were considered that had a chance of being implemented based on NRCS conservation programs (http://www.nrcs.usda.gov/programs/) and/or for which financial incentive programs existed or could be developed. However, there were some scenarios evaluated which could not be realistically implemented, such as converting the watershed to 100% no-till (Scenario E) or converting all cropland to fall tillage (Scenario F). Evaluating these less realistic scenarios provided results that served as benchmark information or helped in understanding model performance. The fall tillage simulation (Scenario F) was thought to represent the worst case scenario for the existing conditions within the watershed, whereas the 100% no-till simulation (Scenario E) represented what was thought to be the best case scenario that could ever be obtained with the existing conditions of the watershed.

Watershed Calibration and Simulation Procedure

The land use and management practices of 1999-2002 (table 1) were considered to represent the existing situation of the watershed. For simulations of existing watershed conditions, 100-year synthetic weather data were used, with the 4-year land use and tillage operation listed in table 1 repeated for a 100-year period during simulations. However, the spatial distribution for this simulation was not fully location-based because data were not available for the type of tillage practiced for each crop field. From representative tillage transect data, the overall percentages of tillage types were known while the exact field-by-field values were not. Thus, tillage type was applied on a random basis to each field to come up with the total amount of conventional, mulch, and no-till percentages.

Annual average (1979-2002) flow and sediment data collected at the Fort Jennings USGS gage station were used to calibrate AnnAGNPS simulated long-term annual average runoff and sediment loss. The long-term annual average data were chosen for calibration for the following reasons: 1) long-term annual average information is needed for evaluation of the alternative management scenarios; 2) historical weather data were not available, and 100-year synthetic weather data were used for simulations (while synthetic weather data would not match the historical weather data for an individual event, long-term synthetic weather statistics should reflect historical weather statistics); 3) land use, crop rotation, and management practices during the simulation period changed from year to year, and it was very difficult, at this watershed scale, for AnnAGNPS to characterize the annual changes occurring in the watershed; 4) evaluation and calibration of the subsurface component of AnnAGNPS was impossible because of the difficulties in separating subsurface flow from the Fort Jennings USGS gage records.

Land use and field management for the existing conditions were assumed to represent the calibration period of 1979-2002. Trial and error were performed to adjust AnnAGNPS parameters of drainage rate, curve numbers, and management practices to produce the long-term annual average runoff and sediment loading close to those measured at the Fort Jennings USGS gage at the outlet. The range of adjustment of input parameters was limited to what was recommended in the references for this specific situation; thus, no specific calibration target was set up during calibration. Calibration was stopped when input values reached their limited values. A drainage rate of 12.7 mm/day was used based on local conditions and calibration.

Following the calibration and simulation of existing conditions (baseline), the various alternative agricultural management scenarios described above were then simulated. Simulations of alternative agricultural management scenarios were then compared with the simulation of the baseline condition to evaluate their effects on erosion and sediment delivery in the watershed. Each management scenario was then evaluated within the watershed for both drained and un-drained conditions.

RESULTS AND DISCUSSIONS

Model calibration results are presented in table 2. Results of runoff, soil erosion, sediment yield, and sediment loading with and without use of subsurface drainage for alternative scenario simulations are given in table 3. Soil erosion refers to the amount of soil detached from the landscape; sediment yield refers to the amount of soil/sediment that moves through the landscape and reaches the channel; and sediment loading refers to the amount of soil/sediment that moves through stream channels and reaches the watershed outlet. Sediment loadings for alternative agricultural management scenarios as percentages of existing conditions are also given in table 3.

MODEL CALIBRATION

Annual average runoff (1979-2002) collected at the Fort Jennings USGS gage station was 254 mm. After a trial and error calibration, the AnnAGNPS simulated 100-year annual average runoff was 254 mm, which consisted of 163.6 mm from direct surface runoff and 90.4 mm from subsurface quick return flow (table 2). Subsurface drainage flow was the major component of subsurface quick return flow. Evaluation and calibration of the subsurface component of AnnAGNPS was not possible because there was no way to separate subsurface flow from the data collected at the Fort Jennings gage station. For a comparison, a simulation without subsurface drainage predicted that the annual average runoff at the Fort Jennings gage station was 195.3 mm.

Annual average sediment loading (1979-2002) collected at the Fort Jennings USGS gage station was 0.753 t/ha/yr. After a trial and error calibration, the AnnAGNPS simulated 100-year annual average sediment loading was 0.771 T/ha/yr (table 2). In contrast, when subsurface drainage flow was not simulated, the simulated annual average sediment loading was 0.846 t/ha/yr.

Evaluation and calibration of the model in a more intensive way, such as comparison of annual runoff and sediment, are not possible because historical weather data were not available for this study. In addition, it is not known at this watershed level when and where the land use changed and how the detailed field management operation (including planting, harvesting, and tillage operations) changed during 1972-2002. The 4-year land use and management practices of 1999-2002 (table 1) were assumed to represent the situation of 1972-2002, and they were repeated during the simulation period. Therefore, the calibration of the model is limited to annual average. The annual average calibration is limited in evaluating the performance of the model, but annual average reflects the general trend happening in the watershed over the years; thus, the critical parameters impacting runoff and sediment loadings from the watershed can still be calibrated to better reflect the real situation of the watershed. This calibration is important for this study because those parameters are the basis for additional alternative management scenarios evaluation.

A more intensive calibration and evaluation of the model performance may still be required in future studies. For this kind of study, historical weather data is needed. In addition, to evaluate the subsurface drainage flow, continuously monitored surface and subsurface flow data are needed. Besides historical weather and continuously monitored flow data, detailed watershed land use and field management operations are also very important in model calibration and validation.

EVALUATION OF ALTERNATIVE AGRICULTURAL MANAGEMENT SCENARIOS

A targeted application of 11% new no-till (scenario B) on the most erodible cropland achieved a 25% reduction in

Table 2. Post−calibration model outputs of runoff and sediment as compared to observed values for existing watershed conditions.

Item	AnnAGNPS Simulation	USGS Observation
Watershed annual average direct surface runoff (mm)	163.6	
Watershed annual average subsurface flow (mm)	90.4	
Watershed annual average total runoff (mm)	254.0	254.0
Sediment loading at the watershed outlet (t/ha/yr)	0.771	0.753

sediment loading at the mouth (table 3). As expected, an increase in no-till application achieved a higher sediment reduction. An application of 23.2% of new no-till (scenario C) on the most erodible cropland achieved a 42% reduction, and an application of 35.7% of new no-till (scenario D) on the most erodible cropland achieved a 48% reduction (table 3). However, the increase in sediment reduction was not on the same pace as the increase in no-till application. The first 11% new no-till application to the watershed achieved a 25% reduction, an additional 13.6% increase of new no-till from scenario B to scenario C resulted in an increase of 17% reduction, whereas another additional increase of 13.8% of new no-till from scenario C to scenario D resulted in an increase of only 6% reduction (table 3). Thus, it is important to target the critical areas which had serious erosion first so that cost/benefit can be maximized and non-point source pollution control can be achieved in the most efficient way. However, in reality, implementation of no-till on the most erodible areas is probably not politically or programmatically feasible because this land treatment program relies on voluntary incentives. Thus, a more realistic treatment would be randomly converting a percentage of cropland to no-till. Scenario G was such a case, in which 12.9% of new no-till and 6.9% of new grassland (crop retirement program) were randomly applied to the watershed. Even with a higher percentage of no-till conversion and a new 6.9% of grassland, scenario G achieved only 18% reduction in sediment loading, which is less than that of scenario B (table 3).

Scenario G, which was 12.9% random new no-till and 6.9% random new grassland, achieved an 18% reduction in sediment loading. A more efficient scenario was H, which converted 7.1% of the highest slope areas to grassland and

Table 3. Comparison of scenarios with and without subsurface drains (tile drains) for the Upper Auglaize watershed 100-year simulation.

Scenario			Runoff Volume (mm)			Total Landscape Erosion F (t/ha/yr)	Total Sediment Yield (t/ha/yr)	Sediment Loading at Outlet (t/ha/yr)	Percent of Existing Condition Load (%)
ID	Description[a]	Subsurface Drainage	Surface	Subsurface	Total				
A	Existing (baseline) condition	Without	195.1	0.3	195.3	6.980	2.713	0.846	100
		With	163.6	90.4	254.0	6.207	2.422	0.771	100
B	11% of the watershed representing the highest eroding cropland areas (9,425 ha.) converted to no-till.	Without	189.7	0.3	190.0	5.105	1.963	0.648	77
		With	157.0	95.0	252.0	4.463	1.724	0.577	75
C	23.2% of the watershed representing the highest eroding cropland areas (19,945 ha.) converted to no-till.	Without	183.2	0.3	183.5	3.981	1.526	0.517	61
		With	149.4	100.3	249.7	3.436	1.328	0.449	58
D	35.7% of the watershed representing the highest eroding cropland areas (30,655 ha.) converted to no-till.	Without	177.0	0.3	177.3	3.634	1.398	0.469	55
		With	142.1	105.4	247.6	3.115	1.212	0.404	52
E	All cropland no-tilled.	Without	166.7	0.3	167.0	3.032	1.172	0.392	46
		With	129.2	114.1	243.3	2.580	1.014	0.331	43
F	All cropland fall plowed, freshly cultivated	Without	246.6	0.2	246.8	11.516	4.468	1.375	163
		With	227.4	48.5	275.9	10.785	4.179	1.313	170
G	12.9% of the watershed representing random cropland areas (13,499 ha.) converted to no-till and 6.9% (5,862 ha) converted to grassland.	Without	183.1	0.3	183.4	5.703	2.219	0.695	82
		With	149.7	100.4	250.0	5.053	1.978	0.630	82
H	7.1% of the watershed representing cropland areas with the highest slope (6,121 ha) converted to grassland.	Without	189.3	0.3	189.6	5.073	1.940	0.628	74
		With	157.4	95.1	252.6	4.556	1.752	0.575	75
I	15.7% of the watershed representing cropland areas with the highest slope (13,499 ha) converted to grassland.	Without	181.7	0.4	182.0	3.532	1.325	0.447	53
		With	149.4	101.2	250.6	3.190	1.207	0.412	53
J	24.5% of the watershed representing cropland areas with the highest slope (21,067 ha) converted to grassland.	Without	174.7	0.4	175.0	2.535	0.939	0.326	39
		With	142.1	106.8	248.9	2.314	0.868	0.304	39

[a] Application of no-till or grassland to the watershed was on a cell basis because cells are the basic computational areas of AnnAGNPS. However, since the size of the area of a cell was determined based on topography, the percentage of no-till or grassland conversion may not be a whole number.

achieved a 25% reduction in loading (table 3). As expected, an increase in grassland application achieved a higher sediment reduction; an application of 15.7% of new grassland (scenario I) on the highest slope areas achieved a 47% reduction in sediment loading, and an application of 24.5% of new grassland (scenario J) on the highest slope areas achieved a 61% reduction in sediment loading (table 3). Similarly, the increase in sediment reduction was not on the same pace as the increase in grassland application. The first 7.1% new grassland application to the watershed achieved a 25% reduction, an additional 9.5% increase of new grassland from scenario H to scenario I resulted in an increase of 23% reduction, whereas an additional 9.7% increase of new grassland from scenario I to scenario J resulted in an increase of 14% reduction (table 3).

Increases in both no-till and grassland would reduce landscape erosion, which in turn would reduce sediment yield and loading (table 3). However, new application of grassland areas is more efficient than new application of no-till areas in sediment reduction. A 25% reduction in sediment loading requires 11% of new no-till application, but 7.1% of new grassland application; a 15.7% new grassland (scenario I) achieved a 47% reduction, whereas 24.5% of new no-till (scenario J) achieved a 42% reduction (table 3). The model as run for this project did not have a riparian buffer or filter strip component. The effectiveness of grass buffers captured in the model represented only the effect of land cover change on erosion and not the benefits that would accrue from any trapping efficiency when practices were positioned adjacent to a stream. Thus the model may have underestimated the effects of these practices, which may provide additional reductions over the benefits stated.

Evaluation of Subsurface Drainage on Runoff and Sediment

Adding subsurface drainage increased total runoff (table 3). Total runoff includes direct surface runoff, subsurface drainage flow, and subsurface lateral flow. AnnAGNPS simulations with subsurface drainage had more total runoff than those without subsurface drainage for all scenarios (fig. 3). Furthermore, adding subsurface drainage reduced surface runoff because subsurface drainage reduced soil water content which promoted more infiltration. Zucker and Brown (1998) summarized studies on subsurface drainage and concluded that subsurface drainage could reduce surface runoff by about 29% to 45% at a field scale. Surface runoff of all alternatives was reduced by 16% to 23% by subsurface drainage in this watershed study. The UA watershed is 85,812 ha in size, and about 74% of which is cropland. The great benefit of reducing surface runoff with a subsurface drainage system was the reduction of landscape soil erosion. Studies done in Illinois showed that fields with intensive subsurface drainage installed had little soil erosion (Mitchell et al., 2001). AnnAGNPS simulations with subsurface drainage had less soil erosion than without subsurface drainage for all scenarios (fig. 4). Less soil erosion led to less sediment loading at the watershed outlet. Sediment loadings under drained conditions were always less than loadings under un-drained conditions for otherwise identical land use (table 3). The sediment loading of all alternatives with subsurface drainage was about 84% to 93% of the loading without subsurface drainage (table 3). The survey of subsurface drainage studies conducted by Zucker and Brown (1998) concluded that subsurface drainage could reduce sediment losses by 16% to 65% at a field scale. The sediment reduction by subsurface drainage in the UA watershed simulation seemed low as compared with the studies summarized by Zucker and Brown (1998); howver, this study was conducted at a watershed scale, and only 74% of the watershed was cropland.

Summary and Conclusions

Subsurface lateral flow and subsurface drainage components were developed within AnnAGNPS to more effectively evaluate the impact of management practices for watersheds that produce a significant amount of subsurface flow. Subsurface lateral flow was determined using Darcy's

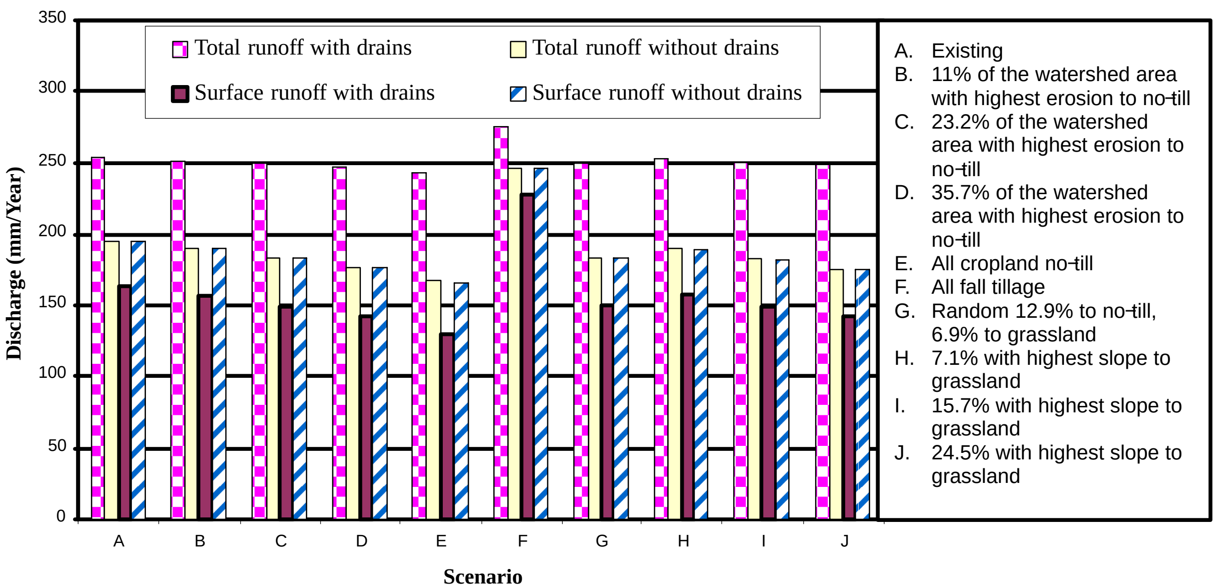

Figure 3. Comparison of simulated average annual runoff with and without subsurface drains for the Upper Auglaize watershed for a 100-year simulation.

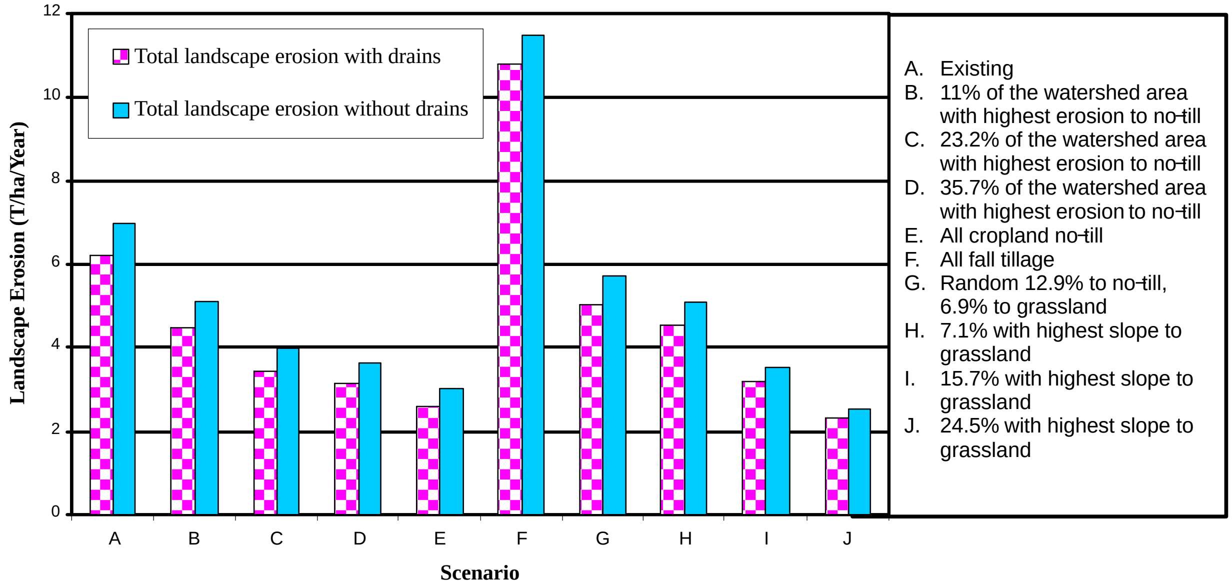

Figure 4. Comparison of simulated average annual landscape soil erosion with and without subsurface drains for the Upper Auglaize watershed for a 100-year simulation.

equation, and subsurface drainage was determined using Hooghoudt's equation. The model incorporated several options to determine subsurface drainage based on the user's availability of information on subsurface drainage systems. Subsurface lateral flow and subsurface drainage were assumed to occur only when a perched water table develops. The model was applied to the UA watershed non-point source modeling project to evaluate alternative agricultural management scenarios in reducing soil erosion and sediment loading. Application to the UA watershed non-point source modeling project illustrated the use of AnnAGNPS for assessing the impact of BMPs and subsurface drains on total runoff and sediment loadings. The ability of AnnAGNPS to simulate subsurface flow was critical for the UA watershed non-point source modeling project because of the significance of subsurface drainage in the hydrology of the watershed and corresponding sediment transport. The model was sensitive to the hydrologic impacts of subsurface drainage in reducing the sediment loading from the watershed. However, because of limited monitoring data, evaluation of model performance on subsurface drainage prediction was not performed in this study.

Adding subsurface drainage increased total runoff, but reduced surface runoff, which in turn reduced soil erosion and sediment delivery from the watershed. Sediment loadings under drained conditions were less than loadings under un-drained conditions in all simulated scenarios; and the sediment loadings for drained conditions were reduced by 7% to 16% compared with un-drained conditions. These results suggest that subsurface drainage practice provides not only a valuable crop production benefit, but also significant erosion and sediment control benefits. The model also indicated that a conversion of the most erodible cropland to no-till (11%) or a conversion of the highest slope areas to grassland (7.1%) could reduce the sediment loading transported from the watershed to 75% of the existing condition. Application to the watershed of various areas of no-till or grassland or a combination of the two could reduce sediment loadings to a range of 39% to 82% of the existing condition in the UA watershed. This study demonstrates that the addition of subsurface lateral flow and subsurface drainage components to AnnAGNPS provides an efficient means of quantifying the impact of subsurface drainage on watershed hydrology, soil erosion, and sediment transport. Therefore, enhanced AnnAGNPS has significant potential value for evaluating future best management practices for subsurface drained watershed.

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